Summary of pn Junction

Built-in potential: \[ V_0 = V_T \ln \left( \frac{N_A N_D}{n_i^2} \right) \]

Under forward bias:

I-V curve: \[ I = I_S \left( e^{V/V_T} - 1 \right) \]

Diffusion capacitance: \[ C_d = \left( \frac{\tau_T}{V_T} \right) I \]

Under reverse bias:

Negligible current, \[ I = -I_S \]

Depletion capacitance: \[ C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{V_0}}} \]

Other important parameter:

Depletion Width: \[ W = \sqrt{\frac{2 \varepsilon_S}{q} \left( \frac{1}{N_A} + \frac{1}{N_D} \right) (V_0 - V)} \]
Many Applications of Diodes

LED (Light-Emitting Diode)  
LED Lighting  
Laser Diode

Solar Cells (PV)  
Photodiode  
OLED
How Many Diodes are in a Smart Phone?
How Many Diodes are in a Smart Phone?

UNLOCKING THE NEXT DECADE

2017

Beginning of the 3D imaging era

2027

Yole's expectations

How Many Diodes are in a Smart Phone?

**IPHONE X – TRUEDEPTH MODULE ANALYSIS – WORKFLOW HYPOTHESIS**

1. ToF Proximity sensor (+ Inertial sensor ?)
   Activity/Human detection

2. Flood illuminator + IR camera:
   Face + Eyes detection (day and night conditions)

3. DOT projector + IR camera:
   Face Recognition (FR)

3 Steps for unlocking

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Diode I-V Curve (Forward)

- I-V curve at high current
- **Approximate** "turn-on" voltage at 0.7V for Si
  - There is no exact turn-on voltage
  - Current keeps increasing exponentially
- I-V curve at low current
- Soft increase at forward bias
- Can see reverse saturation current, $I_S$
Reverse Breakdown

- At sufficiently large reverse bias voltage, current starts to increase dramatically
  - Due to avalanche breakdown or quantum mechanical tunneling
  - Breakdown voltage can be designed
  - Sometimes used as a voltage limiter
An ideal diode only allows current to flow in one direction

- Short circuit for \( V > V_{ON} \) (~0.7V for Si)
- Open circuit for \( V < V_{ON} \) (as well as reverse bias)
Exact Solution with Real Diode I-V

**Simple model:**

\[ V_D = 0.7 \, V \]

\[ I_D = \frac{V_{DD} - 0.7}{R} \]

**Precise model**

\[ I_D = I_S \left( e^{\frac{V_D}{V_T}} - 1 \right) \approx I_S e^{\frac{V_D}{V_T}} \]

**KVL:**

\[ V_{DD} = I_D \cdot R + V_D \]

**Example:**

\[ V_{DD} = 2 \, V, \; I_S = 10^{-15} \, A, \; R = 1 \, k\Omega \]

\[ \Rightarrow \text{Find out } I_D \]

**Load line**

\[ V_D = \frac{I_D \cdot R + V_D}{I_D} \]

\[ V_D = 0 \Rightarrow I_D = \frac{V_{DD}}{R} \]

**Iterative:**

1. \( V_D = 0.7 \, V \), \( \Rightarrow \) \( I_D = \frac{2 - 0.7}{1 \, k\Omega} = 1.3 \, mA \)
2. Find \( V_D \) so \( I_D = 1.3 \, mA \)
3. \( V_D = V_T \cdot \ln \left( \frac{1.3 \, mA}{I_S} \right) = 0.72 \, V \)
4. \( I_D = \frac{2 - 0.72}{1 \, k\Omega} = 1.28 \, mA \)
\[ I_a = I_s \cdot e^{\frac{V_b}{V_T}} \]

\[ V_b = V_T \ln \left( \frac{I_a}{I_s} \right) \]
**Half-Wave Rectifier**

Ideal

\[ D \]

\[ v_s \]

\[ v_o \]

\[ v_o = v_s - 0.7 \text{V} \]

\[ v_o = 0 \]

\[ v_o \]

\[ v_D \]

\[ v_s \]

\[ \text{Throw away} \]

\[ \text{Slope} = 1 \]

\[ ON \]

\[ OFF \]

\[ 0.7 \text{V} \]
Full-Wave Bridge Rectifier

Transformer

Positive cycle $D_1, D_2$ on

Negative cycle $D_3, D_4$ on

$\leftarrow$ select transformer with desired turn ratio
Filter to Remove Ripples

What is the RC time constant in forward bias?
What is RC in reverse bias?

In positive cycle, charged to \( V_p - V_D \)
\( V_c = \frac{Q}{C} \)
Full-Wave Bridge Rectifier with Smoothing Capacitor

Where do you add capacitor?

DC Power Supply

Power transformer
+ ac line 120 V (rms) - 60 Hz

Diode rectifier

Filter

Voltage regulator

Load

Where do you add capacitor?

How does output waveform change?

\[ v_o = v_S - 2v_D \]

RC discharging \( e^{-t/RC} \)

Breakdown voltage = 5V
Peak Detector

- The capacitor is charged to the peak voltage and the output is held at the peak
  - When input > output, diode is ON, charge capacitor to new peak
  - When input < output, diode is OFF. Capacitor holds output at peak
- If you flip the direction of the diode, you get a negative peak detector.
Negative Peak Detector $v_5$

$V_S > V_o$, Diode OFF
$V_S < V_o$, Diode ON

$V_o = V_c$
$V_c = V_S \rightarrow V_S, peak, neg$
$V_o = V_c$
Filter to Remove Ripples

What is the RC time constant in forward bias?
What is RC in reverse bias?

\[ V_S > V_0 - V_D \]

Current through R
\[ I_L = \frac{V_0}{R} \]

\[ V_{on} = \text{ON resistance of diode} \]

\[ \alpha = (1 - e^{-t/T}) \]
Full-Wave Bridge Rectifier with Smoothing Capacitor

Where do you add capacitor?

How does output waveform change?

DC Power Supply

Diode rectifier

Filter

Voltage regulator

Load
Level Restorers

- Diode turns on initially and charges the capacitor to the AC voltage.
  - Note that once the voltage starts to drop, the diode turns off.
- The output voltage is therefore level shifted by the DC voltage held on the capacitor.
- In this case the voltage excursions are now negative and never rise above zero!
  - If a load is connected, then the capacitor should be large enough to minimize droop.
Level Restorers

- If we now flip the direction of the diode, the current will only flow during the negative half cycle, charging the capacitor now in the opposite direction.

- Then output is now lifted by the DC voltage stored on the capacitor. The voltage will now always remain positive and never go below zero!

1. **Diode OFF**, \( V_o = V_s - V_c = V_s \)  
   Cap C not charged yet, \( V_c = 0 \)

2. **Diode ON**, \( V_c = V_s \), \( V_o = V_s - V_c = 0 \)

3. **Diode OFF**, \( V_c = -V_p \)  
   \( V_o = V_s - V_c = V_s + V_p \)
• If we rectify the above voltages, we can generate positive or negative DC voltages of twice the magnitude. This is a voltage doubler!
Use an op-amp to make circuit precise

$V_I > 0$, $V_A = A_{open} (V_I - V_-)$ → large positive voltage
Diode ON, $\Rightarrow V_- = V_I$ by feedback
$V_0 = V_- = V_I$, $V_A = V_0 + V_D$

$V_I < 0$, $V_A = A_{open} (V_I - V_-)$ → large negative voltage
Diode OFF, no feedback

$V_0 = 0$
Small Signal Resistance

\[ i_D = I_S \left( e^{\frac{V_D}{kT}} - 1 \right) \approx I_S \frac{V_D}{V_T} \]

DC circuit

Bias point \( Q \)

Tangent at \( Q \)

Stope = \( \frac{1}{r_d} \)

Current

Time

Voltage

For small signal

Replace transfer curve with tangent
slope $= \frac{\Delta i_D}{\Delta U_D} = \frac{1}{R_d}$

$R_d = \frac{\Delta U_D}{\Delta i_D} = \left( \frac{1}{\frac{d\Delta i_D}{dU_D}} \right) = \left( \frac{i_D}{V_T} \right) = \frac{V_T}{i_D}$. \hspace{1cm} \text{at room temp}

$i_D = I_s e^{\frac{U_D}{V_T}}$

$\frac{d\Delta i_D}{dU_D} = I_s \cdot \frac{1}{V_T} e^{\frac{U_D}{V_T}} = \frac{1}{V_T} \left( I_s e^{\frac{U_D}{V_T}} \right) = \frac{i_D}{V_T}$

Symbol convention

$I_D = DC$ current

$i_D = AC$ current

If diode is biased at $I_D = 1 mA$

$R_d = \frac{V_T}{I_D} = 26 \Omega$

$RC = R_d \cdot C$
Photodiodes

Thu: Video. No Class
Solar (Photovoltaic, or PV) Cells

- Operating in the 4\textsuperscript{th} quadrant of the I-V curve → It generates power!

- Key parameters:
  - Open circuit voltage, $V_{OC}$
  - Short-circuit current, $I_{sh}$
  - Fill factor